A GENERATIVE APPROACH TO ESTIMATE EFFECTS OF SAFETY SYSTEMS FOR REAR-END COLLISIONS USING ASSTREET

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ABSTRACT

Estimating the benefits of advanced safety systems before introducing to markets is useful to develop and enhance the systems effectively. Several estimation methods have been proposed to date. Some are based on comprehensive accident data such as those of NASS-CDS. Others are based on proving-ground test results. However, actual accidents present much more permutations and configurations of striking and struck vehicles than those. Furthermore, driver behavior varies among cases.

This paper presents a proposal of a novel method that addresses the issues described above. First, a virtual traffic flow that represents an actual one is created. Then, the way in which an active safety system is expected to play its role in accidents happening in traffic is measured. The Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET) was used to generate road environment, vehicle movements, and driver behavior. In order to show the usefulness of the method, a pre-collision system (PCS) with forward collision warning (FCW), pre-collision brake assist (PBA), and pre-collision brake (PB) functions were applied as the active safety system. The procedure is the following.

A virtual traffic flow was created. On a simple road environment with intersections and traffic signals, numerous vehicles run under traffic rules on ASSTREET. The vehicles' speed distribution and the duration of the stopping period were adjusted to match realistic driving data measured on roadways, by the road parameters such as speed limits and the distance between intersections.

Next, rear-end collisions in the virtual traffic flow were created. Driver errors and braking reaction after noticing the collision danger were incorporated into the virtual driver behavior. Because most of the driver errors in rear-end collisions are attributable to inattention, the inattention period and the brake reaction time with a convincing distribution were given to the virtual drivers. The braking deceleration distribution, which is also necessary characteristics for pre-collision reconstruction, was obtained using our driving simulator through the ACAT (Advanced Collision Avoidance Technology) program with NHTSA (National Highway Traffic Safety Agency). The distribution of the combination of striking vehicle speed and struck vehicle speed agreed well with actual data. Consequently, rear-end collisions in the simulation were regarded as representing actual ones.

Finally, the benefit of PCS was estimated. Rear-end collisions in the virtual traffic flow were generated by vehicles with no active safety systems. After collecting all rear-end collision pairs of striking and struck vehicles, a PCS was installed in striking vehicles. Then the simulation was repeated. Comparing the results obtained with and without use of the system clarifies the PCS benefit.

The advantage of this method is that a mass of rear-end collisions enables evaluation of PCS' specification differences quantitatively. Results clearly indicate circumstances in which the system is expected to function effectively.

Although the current simulation is considered as covering most of rear-end collisions that people might happen to encounter, such scenarios as avoidance by steering, collision during negotiation of a curve, and collision with a cutting-in vehicle have not been simulated yet. Those will be addressed in the near future.

INTRODUCTION

Estimating the benefits of advanced safety systems before introducing to markets is useful to develop and enhance systems effectively. The basic approach of estimation is to take advantage of accident data and simulate a collision to determine whether accidents could have been avoided with the system equipped with a vehicle. The main problem of the approach is that it is difficult to acquire cases with detailed kinetic information needed for the simulation. The other problem is that accidents seldom occur in actual traffic. For instance, in the 100-car study conducted by National Highway Traffic Safety Administration (NHTSA), only 27 rear-end collisions were observed among their records of one hundred vehicles during one year [1].

Two kinds of approaches were proposed to solve the problem. One approach is to make use of the in-depth accident data [10] which has been accumulated year by year. However, lack of detailed driver behavior in the data remains to be a major disadvantage. The other approach takes advantage of near-crash cases instead of accident cases [11] [12] [13]. Although near-crashes occur more frequent than accidents, their amount is still limited. Even in the 100-car study, only 60 cases were available for analyses [11].

Therefore, a generative approach is proposed. This paper first describes how a rear-end collision model was built based on the analysis of ITARDA (Institute for Traffic Accident Research and Data Analysis) micro data. Then, it describes how virtual rear-end collisions were generated and the results are compared with actual statistics. In the last section, the benefit of the proposed method is demonstrated by applying it onto a PCS (pre-collision system). The micro data analysis result was brought from the collaborative research with ITARDA, "Investigation of Human Factors in Traffic Accidents for Driver Assistance systems". ASSTREET (The Advanced Safety System & Traffic REaltime Evaluation Tool) was used to generate virtual collisions.

ACCIDENT MODEL

Kinetic Model

A simple kinetic model with no human-related factors is considered to simulate a rear-end collision. In terms of geometry, a collision is the state in which the distance between objects becomes zero. Therefore, any vehicle-to-vehicle collision process can be described with their trajectories. For further simplification, rear-end collisions are assumed to be caused between only two vehicles on a straight road. Then, a collision is expressed as a crossing point of the two vehicles' trajectories, as shown in Figure 1.

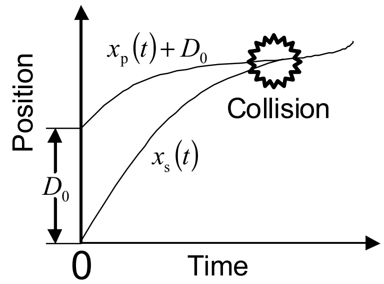


Figure 1. Rear-end collision model.

Equation (1) describes a simplified rear-end collision model.

$$\exists t, (x_p(t) + D_0) - x_s(t) = 0, \text{ where } x_p(0) = x_s(0) = 0 \quad (1).$$

Here, x_p and x_s are the time-variant positions of a leading vehicle and a following vehicle respectively, their positions at time 0 is 0. D_0 is the initial distance between the vehicles.

The equation indicates that x_p, x_s and D_0 are the least variables to describe a rear-end collision. Although the model assumes that both vehicles' lengths are zero, substituting zero length for non-zero length will not affect the calculation. If three variables x_p, x_s, and D_0 of all rear-end collisions occurred in the real world are known, then kinetic models are consequently created and the benefits of the rear-end collision prevention systems could be assessed precisely.

However, as it is not realistic to know them, ITARDA micro data analysis and normal driving data analysis were used for the substitution. The procedure is addressed in the next section.

Accident Data Analysis

To clarify the vehicles' behavior before rear-end collisions, 98 of ITARDA micro data were analyzed. The result is shown in Figure 2.

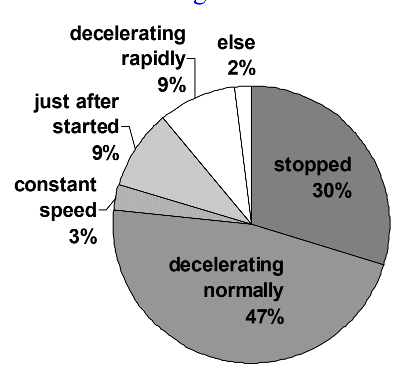


Figure 2. Driving behavior of leading vehicles before crashes (Source : ITARDA)**.**

It was found that more than 90% of the leading vehicles were regarded as normal driving maneuvers. They were either stopped, decelerating normally, moving at constant speed, or had just started. Their velocity before starting deceleration is also distributed within a normal range of approximately from 40 to 70 km/h. These facts indicate that the leading vehicle behavior x_p could be replaced with the normal driving behavior data. The same conclusion is reported in the analyses conducted by ITARDA [2].

Considering an actual collision scene, following vehicle behavior x_s would be divided into four sequences. They are initial state, inattentive state, reaction state, and evasive braking state, as depicted in Figure 3.

The initial state consists of distance D_0 and initial velocity v_0. It should be noticed that both are the representatives of normal driving.

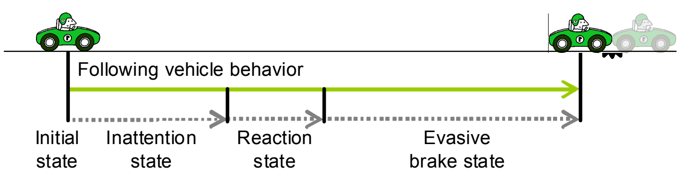
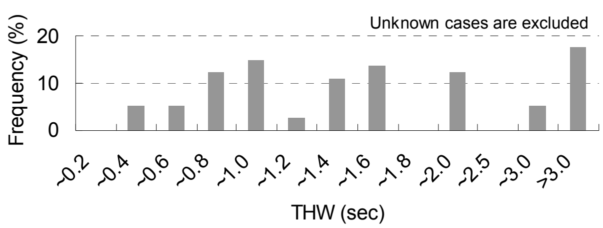
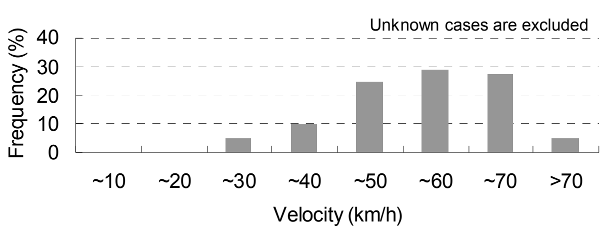


Figure 3. Driver state sequence of a following vehicle.

Then, as shown in Figure 4, the distance D_0 should be distributed approximately 1-2 seconds in terms of the Time Head Way (THW) and the velocity v_0 should be distributed mainly from 40 to 70 km/h.



(a) Time head way before collision danger was noticed



(b) Following vehicle's velocity before collision danger was noticed

Figure 4. Initial states of the following vehicles.

The following vehicle behavior x_s should be described as Equation (2), using four variables: the initial velocity v_0, inattention period λ, reaction time τ and the evasive deceleration by braking $a(t)$. For simplification, it is assumed that the vehicle maintains at a constant velocity when the driver is in inattentive state. Therefore when the braking starts, $a(0)=0$.

$$x_s = v_0 t + \int\int_0^t a_s(t)\,dt\,dt,$$
$$a_s = \begin{cases} a(t-\tau-\lambda) & t-\tau-\lambda \geq 0 \\ 0 & \text{otherwise} \end{cases} \quad (2).$$

In summary, the rear-end collision model is defied by Equation (1) and by Equation (2).

As for the leading vehicle behavior x_p, the initial distance D_0 and the initial velocity v_0 can be identified with those data during normal driving.

The other variables in the model, those are, the inattention period λ, the reaction time τ, and the evasive deceleration by braking a(t) could not be measured in normal driving, but can be identified by a driving simulator experiments, etc.

GENERATE VIRTUAL ACCIDENTS

Generation Process Overview

As the leading vehicle behavior x_p, the initial distance D_0 and the initial velocity v_0 are highly correlated, it is necessary to assign an appropriate joint probability distribution for the calculation. To solve the problem, The Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET) had been developed and introduced.

As depicted in Figure 5, ASSTREET is based on a traffic simulator which includes a driver model [4] [6] and a virtual road environment. The driver model generates plausible behavior in response to traffic situations by simulating drivers' internal processes of perception, cognition, judgment, and operation.

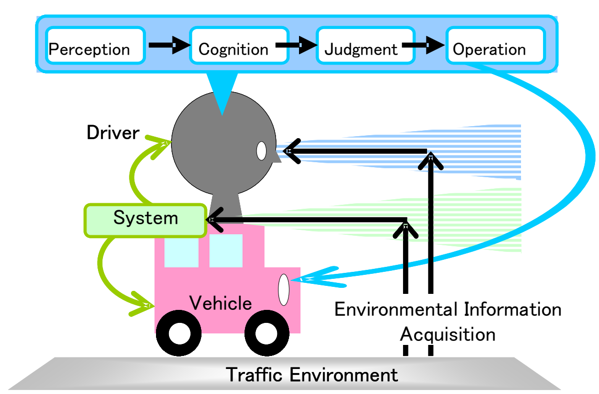


Figure 5. Advanced Safety System & Traffic REaltime Evaluation Tool (ASSTREET).

To simulate a following vehicle behavior before collision feasible in real world, it is essential to assign probability densities to the inattention period λ, the reaction time τ, and evasive deceleration by braking $a(t)$. For the inattention period λ, we adopted the density estimated by Morita et al. [7]. The reaction time τ and the evasive deceleration by braking $a(t)$ are modeled based on results obtained from driving simulator (DS) experiments [8]. Here, as shown in Figure 6, evasive deceleration by braking $a(t)$ is approximated by jerk j and maximum deceleration d_{max} for easier calculation. Then, the deceleration is reconstructed from the probability densities of both parameters.

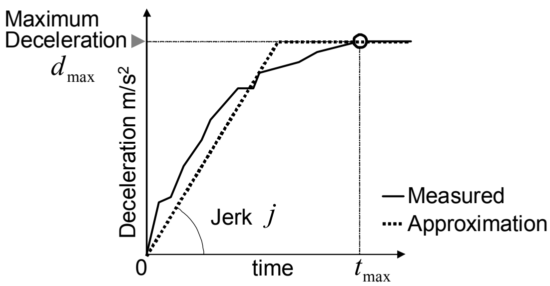


Figure 6. Approximation of evasive braking.

The following steps and Figure 7 explain the simulation procedure.

A. Normal traffic flow simulation process

Simulate a normal traffic flow using ASSTREET under the road environment which will be discussed in the next subsection.

B. Collision generative simulation process

B-1. Select an arbitrary pair vehicles which have leading -following relation.

B-2. Assume a parallel street. On the street, just the selected pair of leading-following vehicles is running.

B-3. Substitute the following vehicle behavior on the parallel street for inattentive driver's behavior defined as Equation (2).

B-4. Save the pair of vehicles' kinetic information as one virtual accident if they collide.

B-5. Repeat calculation from step B-1 to B-4 till sufficient collisions are accumulated.

The collision generative simulation was performed at the back of the normal traffic flow simulation so that the occurred collisions do not spoil the normal traffic flow.

The conspicuous benefit of the separation is described here. The existing simulator donates human errors to the drivers in the virtual traffic and collects the collisions when they happened during the calculation, which is a time consuming effort [3]. On the contrary, the collision generative simulation can generate a lot of virtual accidents in a short time.

In fact, as the parallel simulation is done for different pairs or sampling at different timing, two hundred thousand virtual accidents, which is roughly equivalent to the number of rear-end collisions occurred in a year in Japan, were generated within 20-hour using a Xeon X5482 3.2 Hz processor (Intel Corp.) and 4 GB memory.

Road Environment Model and Its Validation

To simulate a normal traffic flow, it is necessary to apply an appropriate road environment into ASSTREET. As it is apparently impossible to reproduce whole road environment across the country, factors affecting the rear-end collision should be considered.

There are two clues to determine the factors. One is that the collision model treats only longitudinal motion. The other is that the majority of the leading vehicles are stopping or decelerating before collisions. These facts suggest that the essential factors are the velocity change that represents decelerating to a stopping state.

The road environment was modeled by two steps. First, a base structure of the road environment was determined. A street with intersections controlled by traffic signals permitting right and left turns as shown in Figure 8 is adopted. The street also has a speed limit for each section. The street will naturally induce vehicles to decelerate and to stop.

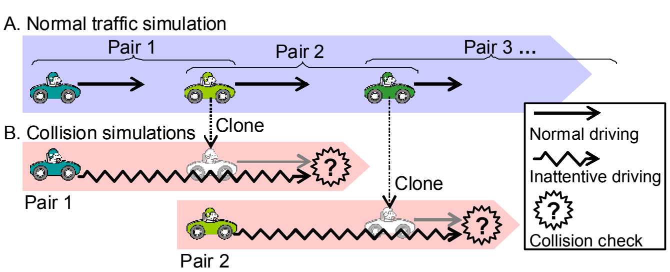


Figure 7. Simulation procedure.

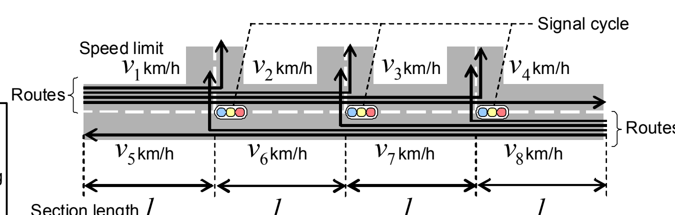
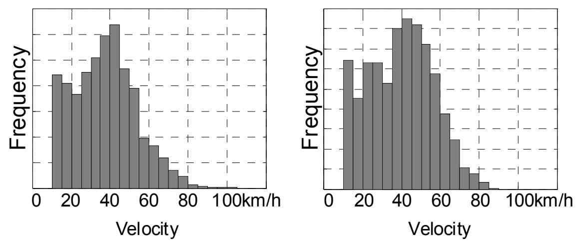


Figure 8. Virtual traffic.

Then in the second step, the section length, speed limit, signal cycle and amount of traffic flows were adjusted referring to the analytical result of naturalistic driving behavior database [9], which is provided by the Research Institute of Human Engineering for Quality Life (HQL).

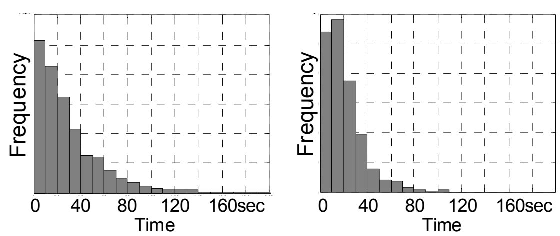
Two properties were used to assess the reproducibility. One is the histograms of the velocity before deceleration and another is the stopping period. Figures 9 and 10 present comparisons between calculation and the analytical result of the naturalistic driving behavior database (DB).

As for the histograms of the velocity before deceleration, though simulation result has more peaks than the naturalistic driving behavior database, both have the same maximum peak at around 40 km/h.



(a) Naturalistic driving DB (b) Simulation result

Figure 9. Comparison of the velocity before deceleration.



(a) Naturalistic driving DB (b) Simulation result

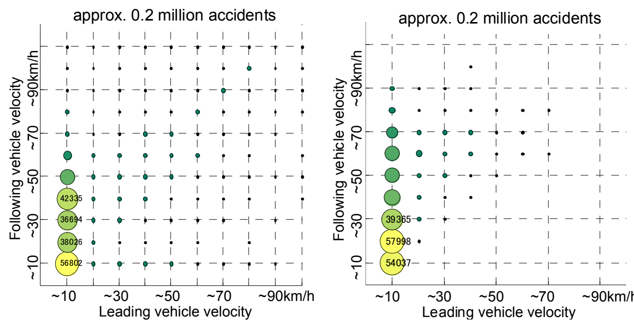
Figure 10. Comparison of the stopping period.

As for the histograms of the stopping period, though simulation result has a peak slightly longer than the naturalistic driving behavior database, and simulation result shows narrower time range than the naturalistic driving behavior database, both results show the similar distribution.

The road environment model is considered to reproduce the actual traffic flow well.

Collision Representation and Its Validation

To validate the generated collision counts, the simulation result is compared with the nationwide traffic accident statistics in Japan compiled by ITARDA. The statistical attribute shown here for comparison is the distribution of velocities when the leading vehicle driver and following vehicle driver recognized collision danger. Figure 11 shows the collision count distributions.



(a) Rear-end collision statistics (2008, Source : ITARDA) (b) Simulation result

Figure 11. Accident distribution comparison.

For the simulated data, the velocity of the leading vehicle at impact is used as substitution and the initial velocity of the following vehicle is used as substitution. It can be seen that both have a majority in a range less than 10 km/h of leading vehicle velocity. When compared by the following vehicle velocity, the simulation result shows a good resemblance to the actual statistics. Both have a peak at the low-velocity range and decrease towards high velocity.

For the area in which both vehicles have low velocity, the simulation result has more collisions than the actual statistics. It is known that the traffic accident statistics is based on accidents reported to the police by drivers. It is also known that drivers tend not to report to the police for trivial collisions [1]. The difference may be derived from the fact.

PCS BENEFIT ESTIMATION

Specification difference Study

As the generated collisions have kinetic histories, the benefit of the safety system can be estimated by adding a system effect onto the following vehicles. Three different PCS specifications; A, B and C were examined. Here,

System A. The system activates just Forward Collision Warning (FCW). When collision risk is judged increased, FCW issues an alarm.

System B. Pre-collision Brake Assist (PBA) is added to System A. PBA is activated after FCW and assists a driver’s braking depending on the amount of his or her braking.

System C. Pre-collision Brake (PB) is added to System B. PB is activated when collision is judged unavoidable. It automatically brakes irrespective of a driver's braking.

The onsets of FCW, PBA, and PB are shown in Figure 12. To understand their difference easily, functions are assumed to be activated for full speed range. The sensors equipped to vehicles are also assumed to function with no error and with no false detection.

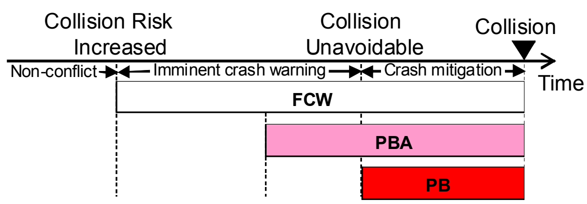


Figure 12. Onsets of FCW, PBA and PB.

Figure 13 shows the result. The benefit is compared by relative speed.

It can be seen that System A (FCW) shows higher collision avoidance ratio in lower speed range and System B (System A+PBA) helps System A for all speed range. System C (System B+PB) is expected to show higher reduction than System A and System B do without doubt, its benefit is shown as speed range expansion rather than as reduction expansion.

Thus, the proposed method enables to compare the system difference quantitatively.

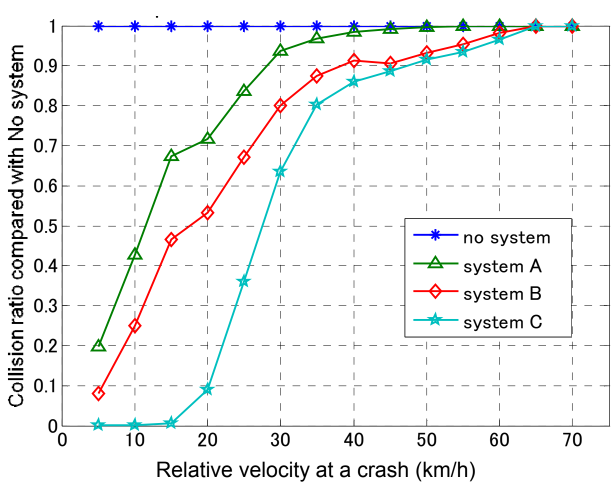


Figure 13. Collision avoidance ratio comparison.

Sensitivity Evaluation Study

Unlike passive safety systems, most of the active safety systems have functions to affect drivers. Therefore, driver properties are considered to have impacts on system benefit estimation. Furthermore, driver properties are usually identified not in actual accidents but in proving ground or driving simulator experiments. Although subjects for these experiments are chosen carefully, the measured properties may contain some bias compared to those in actual collisions. In this section, the driver property influence is addressed which can only be achieved by simulation. Figure 14 presents the results. The vertical axis shows the ratio compared with System A, B and C without offset.

Figure 14 (a) shows the effect of the inattention period λ. The result indicates that the effect is small for all systems. The reason is considered as follows. As inattention period gets longer, the collision count of no system increases, but is soon saturated. However, drivers are assumed to react to the warning in System A, B and C before inattention period ends, collision count will not be affected so much by the inattention period extension. The result reflects the mechanism.

Figure 14 (b) shows the effect of the reaction time τ. The result indicates that the effect is large for System A and B, while is small for System C. It is because System A and B depend on drivers' reaction that the reaction time increase consumes the time available for evasive braking. The result of System C indicates that automated brake could compensate drivers' reaction delay.

Figure 14 (c) shows the effect of the jerk of braking j. The result indicates that the jerk affects relatively dull on all systems. It is considered that the deceleration by driver's brake reaches its maximum in a short period, and the jerk has only a slight effect on the total amount of deceleration.

Figure 14 (d) shows the effect of the maximum deceleration d_{max}. The result indicates that the maximum deceleration is the most contributing factor to PCS.

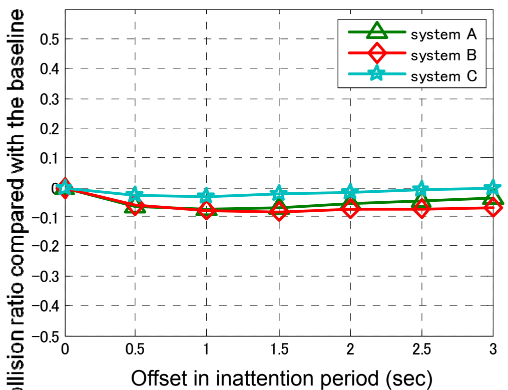
In summary, it became clear that the driver's maximum deceleration is the most contributing factor to PCS, followed by the driver's reaction time.

CONCLUSIONS

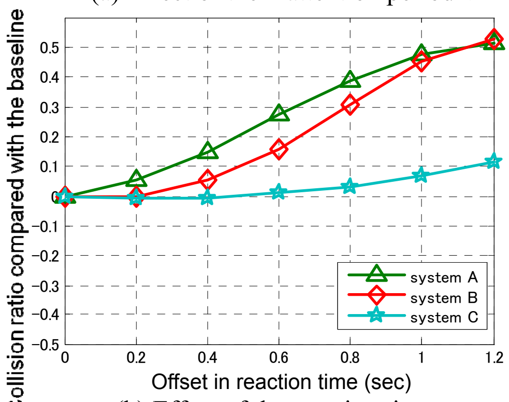
A novel method to estimate the effects of active safety systems was proposed. The characteristics of the method is that rear-end collisions are reproduced through a combination of normal traffic flow simulation process and collision generative simulation process.

For normal traffic flow simulation process, a simulator ASSTREET was introduced. In the generated traffic flow by ASSTREET, leading-following vehicle pairs were selected one by one. Next in the collision generative simulation process, by substituting following vehicle behavior for inattentive driver's behavior, a mass of rear-end collisions were generated.

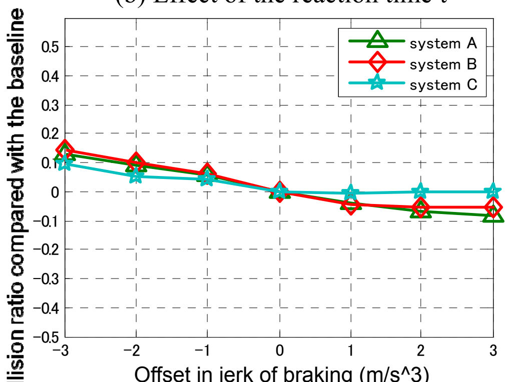
As the collision generative simulation was performed at the back of the normal traffic flow simulation, the collision occurrence does not spoil the normal traffic flow. The results of both processes were verified with actual data.



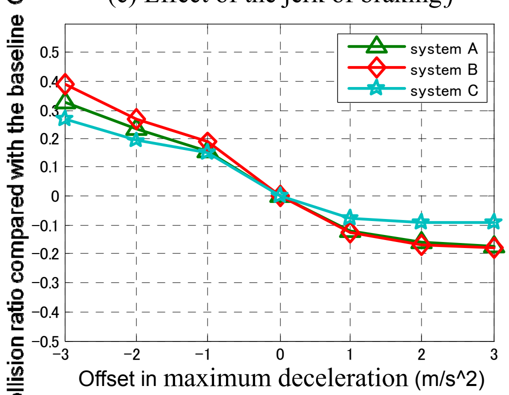
(a) Effect of the inattention period λ



(b) Effect of the reaction time τ



(c) Effect of the jerk of braking j



(d) Effect of the maximum deceleration d_{max}

Figure 14. Sensitivity evaluation.

To demonstrate the benefit of the proposed method, a Pre-collision System (PCS) was applied as an example. Although PCS applied for the evaluation is a virtual one, the result revealed how each PCS function is expected to work effectively. The sensitivity evaluation study revealed that the driver's maximum deceleration is the most contributing factor to PCS, followed by the driver's reaction time.

We believe the simulation is regarded to generate most of rear-end collision patterns, however, certain particular scenarios such as avoiding maneuver by steering, collision during negotiating a curve and collision with a cutting-in vehicle have not been simulated yet. Those issues will be addressed in the near future.

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